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Enhancing the Lift-Off Performance of EMATs by Applying an Fe₃O₄ Coating to a Test Specimen

Bao Liang, Zhichao Li*, Guofu Zhai, Runjie Yang, Xu Zhang, and Steve Dixon

Abstract—Electromagnetic acoustic transducers (EMATs) are non-contact ultrasonic transducers. The transduction efficiency of a particular EMAT on a given specimen is dependent on the lift-off distance, which is the distance between the EMAT coil and the specimen surface. The transduction efficiency drops dramatically with increased lift-off distance, requiring EMATs to be in close proximity to the specimen, usually within a few millimetres. This paper proposes a new EMAT method of applying an Fe₃O₄ coating to the test specimen, and quantitatively studying the enhancement effect of Fe₃O₄ coating on lift-off distance. To eliminate the interference of the electrical and magnetic properties of the tested specimen, a non-magnetic and non-conductive glass specimen is selected. The experimental results on a glass substrate coated with Fe₃O₄ demonstrate the feasibility of EMATs generating and receiving ultrasonic waves through the coating, by a magneto-elastic mechanism. The transduction efficiency of EMATs on an Fe₃O₄ coating does not increase linearly with the bias static magnetic field, and the maximum measured signal amplitude value occurs at a relatively low flux density of ~0.12 T. More specifically, it has been shown the Fe₃O₄ coating can significantly enhance the lift-off distance of EMATs operating at 4 MHz to 8 mm on coated stainless steel. The performance of the Fe₃O₄ coating can be optimized, showing considerable potential to expand the application range of EMATs.

Index Terms—Electromagnetic acoustic transducers (EMATs), lift-off distance, transduction efficiency, Fe₃O₄ coating.

I. INTRODUCTION

ELECTROMAGNETIC acoustic transducer (EMAT) is a type of non-contact ultrasonic transducer, which is capable of generating and receiving ultrasonic waves on metallic materials [1]. EMATs are particularly attractive for some non-destructive testing (NDT) and non-destructive evaluation (NDE) applications, such as online inspection, high-speed scanning, and high-temperature measurement [1]. Due to the electromagnetic coupling mechanism, the transduction efficiency of EMATs depends on the lift-off distance, which is the distance between the EMAT coil and the specimen surface [2-4]. The transduction efficiency reduces dramatically with increased lift-off distance, requiring EMATs to be very close to

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the specimen [3-4]. However, in some conditions, such as when a specimen surface is not flat, or there is specimen vibration, or sample movement, or a requirement to test at high temperatures, the lift-off distance is expected to vary, often up to a large lift-off distance of at least several millimetres.

The maximum effective lift-off distance of EMATs is normally defined with the requirement of a reasonable signal-to-noise ratio (SNR), with some standards-setting this to be around 12 dB. Common methods to improve the SNR of EMATs include: improving the output power of the hardware circuit [5-6] and optimizing the design of the coil and magnet in an EMAT [7-8]. Increasing the excitation current of the EMAT coil is normally a direct and widely used method to improve the SNR [6]. However, more complicated and expensive electronics is needed to generate a large current, and there may be some safety hazards, especially for applications in the oil and gas industry. Compared with improving the output power of the hardware circuit, there are more studies on the optimization design of EMATs, mainly focusing on improving the strength of the static bias magnetic field and the dynamic alternating magnetic field [7-10]. As an example, an optimized Rayleigh wave EMAT can detect defects in rail at the center frequency of 200 kHz with a lift-off distance of 5 mm [9]. An EMAT operating via the magnetostrictive effect can produce longitudinal guided waves in pipes with a center frequency of 120 kHz and a lift-off distance of 50 mm [10]. Ferritic steel pipes that operated at high temperatures often naturally develop a magnetite surface layer (Fe₃O₄), that is highly magnetostrictive and very beneficial for EMAT operation [11]. To meet the needs for operation at large lift-off distances, the ultrasonic excitation frequency of EMATs is usually less than 500 kHz. However, for bulk wave EMATs, the ultrasonic frequency is often required to be in the range of 1 ~ 5 MHz, to ensure a high detection accuracy and good temporal resolution for thickness measurements.

Due to the constraints of instrument performance, EMAT design, and test material properties, it is usually difficult to achieve large lift-off operation at MHz frequencies on specimens that do not have a highly magnetostrictive surface. To provide good lift-off performance with EMATs at MHz frequencies, one solution is the use of magnetostrictive coating technologies to reduce the dependence of the EMAT on the electrical and magnetic properties of a test specimen [12-13]. Another approach is to adhesively bond or attach magnetostrictive foils to a specimen [14]. Nickel, Fe-Ga, Fe-Co, and Terfenol-D alloy have large magnetostrictive strain coefficients, and can be used as foil or coating materials. Materials such as nickel or Fe-Co alloys can be supplied as flexible foils which are ideal for bonding to relatively smooth surfaces [14], whilst Terfenol-D is a brittle material in bulk form, which may be better applied as

powder in a polymer matrix to surfaces that are not perfectly flat [15]. However, high-performance magnetostrictive materials, such as Terfenol-D are relatively expensive consumables, which increases the overall system cost. Earlier research found that Fe_3O_4 is suitable as a coating material [11], because of its small coercivity, low saturation magnetic field strength, and most importantly its relatively significant magnetostrictive effect [16,17]. This paper proposes a new method by applying Fe_3O_4 coating to the tested specimen and quantitatively studying the enhancement effect of Fe_3O_4 coating on lift-off distance.

II. EXPERIMENT PREPARATION

A. Preparation of Fe_3O_4 coating

The Fe_3O_4 coating consists of Fe_3O_4 powder and adhesive. The particle size of Fe_3O_4 powder is $1\ \mu\text{m}$, and the adhesive is a commercial electric insulation varnish [18], which is composed of organic-inorganic polymer and inorganic crystals. The adhesive should have a strong bonding ability to enhance the mechanical coupling between the coating and the specimen. The preparation process for the Fe_3O_4 coating is shown in Fig. 1. The main steps include: (i) Fe_3O_4 powder is poured into the adhesive, and the weight ratio of the powder and adhesive is 1:2; (ii) The Fe_3O_4 powder and adhesive are mixed evenly by stirring with a glass rod, and it is then left to stand for 3 minutes until the bubbles dissipate from the mixture; (iii) Paint the Fe_3O_4 mixture on the specimen surface, with a curing time of 24 hours at room temperature. Since the density of the adhesive ($1.46\ \text{g/cm}^3$) is less than that of Fe_3O_4 powder ($5.18\ \text{g/cm}^3$), more Fe_3O_4 powder will accumulate at the bottom of the coating during curing. After the coating is firmly bonded to the specimen, the coating layer is polished by a 220 grit sandpaper and the final average coating thickness is approximately $200\ \mu\text{m}$.

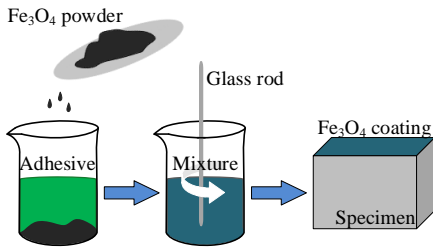


Fig. 1. Preparation of Fe_3O_4 coating on the specimen surface.

Two types of specimens, glass and stainless steel SUS 316 are used to test the Fe_3O_4 coating. The basic material properties are listed in Table 1. The Fe_3O_4 coating has a high magnetic permeability and magnetostriction coefficient but is non-conductive, so the transduction process of the EMAT in the coating only involves the magnetostriction mechanism, and not the Lorentz force mechanism.

Table 1

Material properties of glass and stainless steel SUS 316 at room temperature.

Material	Young's modulus (Pa)	Poisson ratio	Density (kg/m^3)	Electrical conductivity (S/m)	Relative permeability
Glass	0.66e^{11}	0.17	2.27e^3	-	1
SUS 316	2.05e^{11}	0.285	7.93e^3	1.45e^6	1.008

B. Experimental Setup

Fig. 2 shows the experimental setup, which includes an ultrasonic transmitting module, an ultrasonic receiving module, an EMAT, and a coated specimen. The excitation signal to the EMAT coil is a 2-cycle pulse signal with a central frequency of 4 MHz and a peak-to-peak voltage of about 1200 V. The impedance matching circuit also works as a diplexer, so that the EMAT can work in a pulse-echo mode, where the same transducer generates and then detects the ultrasound. The received signal is amplified, filtered, and finally digitized by the oscilloscope. The gain of the preamplifier is 72 dB, and the band-pass of the filter is from 1 MHz to 5 MHz. The received signals are averaged 8 times to improve the signal-to-noise ratio. The EMAT consists of a flat spiral coil and a NeFeB permanent magnet. The magnet's length, width, and height are 35 mm, 25 mm, and 40 mm, respectively. The vertical magnetic flux density at the center of the magnet surface is 0.582T. The diameter of the 40-turns EMAT coil is 12.5 mm, and the insulated wire diameter is 0.12 mm.

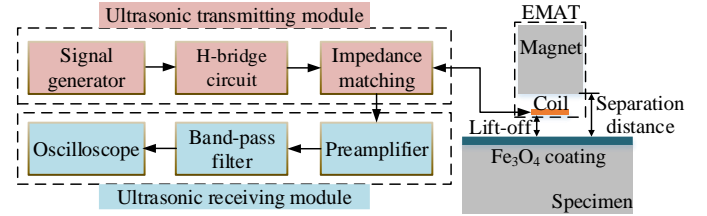


Fig. 2. Schematic diagram of the experimental setup.

It should be noted that there are two distances in the EMAT geometry studied in this paper: (i) the distance between the coil and the specimen – the lift-off, and (ii) the distance between the magnet and the specimen – the separation distance.

III. EXPERIMENTAL RESULTS

A. Influence of the separation distance

Firstly, experiments are carried out on a 20 mm thick glass specimen to which the coating is applied. The lift-off distance of the EMAT coil from the specimen is fixed at 0.1 mm, and the received signals under different separation distances (magnet height above the specimen) are shown in Fig. 3(a). The ultrasonic echo signals can be clearly seen over different separation distances, which demonstrates the feasibility of EMATs generating and receiving ultrasonic waves in the Fe_3O_4 coating. The waveforms include longitudinal waves (L), shear waves (S), and mode-converted waves (C), in which the shear wave is the main component. The shear and longitudinal wave velocities of the glass specimen are 3315 m/s and 5587 m/s, respectively. L_1 is a longitudinal wave generated in the coating by the initial EMAT current pulse and is detected at $t = 2t_l = 2H/v_l$ (v_l is the longitudinal wave velocity and H is the specimen thickness). C_1 is a combination of L - S and S - L transit across the thickness of the specimen and is detected at $t = t_l + t_s = H/v_l + H/v_s$ (v_s is the shear wave velocity). In glass, the shear speed is more than half the longitudinal wave speed, so there are numerous signals between the S_1 and S_2 signals, as shown in the enlarged red box. The paths for these echoes can be determined by the shear and longitudinal wave velocities [19]. Note that the large amplitude at the start of the waveforms up to around 5 microseconds (or main

bang), is electrical noise from the generation pulse being amplified on the receiver electronics and it is not an ultrasonic signal.

The peak-to-peak value of the first shear wave in the received signal and the vertical magnetic flux density on the specimen surface are obtained under different separation distances, as shown in Fig. 3(b). As the separation distance of the magnet increases, the vertical magnetic flux density decreases, while the shear wave amplitude increases first and then decreases. When the vertical magnetic flux density is about 0.12 T, the EMAT has the highest transduction efficiency for Fe_3O_4 coating. As the distance from the permanent magnet to the specimen increases, the magnetic field direction at the coating will also change slightly, being more normal to the surface when the coating is closer to the magnet. It shows the optimal bias magnetic field for magnetostrictive mechanism EMATs should be relatively weak, compared to the optimal field for Lorentz force EMATs, where the largest ultrasonic wave amplitudes would be generated for the largest normal magnetic flux density. This phenomenon has also been reported by other researchers [20], and means that lower-cost permanent magnets with a lower residual magnetic flux density could be selected in the design of magnetostrictive EMATs, rather than the commonly used and more expensive SmCo or NdFeB permanent magnets.

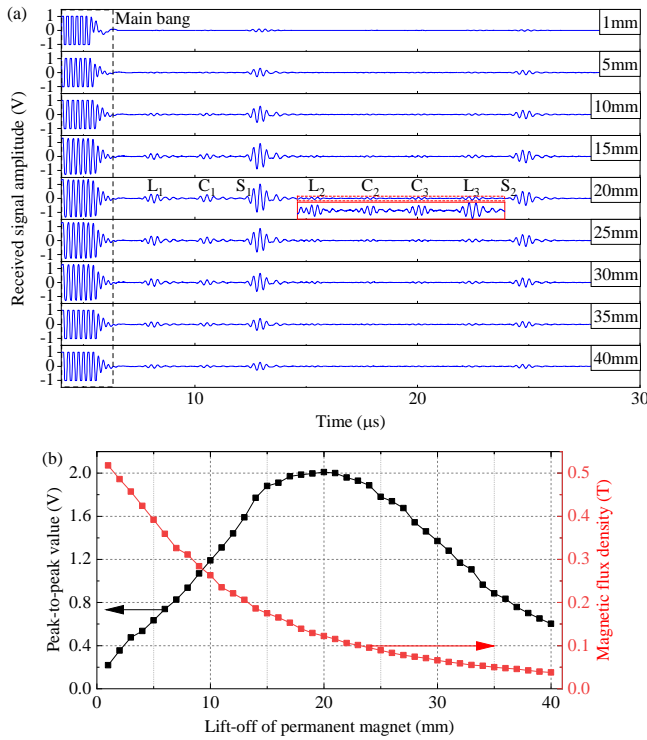


Fig. 3. Experimental results on coated glass specimen under different separation distances. (a) A-scan waveforms, and (b) peak-to-peak values of the first shear waves in the received signal, and the vertical magnetic flux density on the specimen surface.

B. Influence of the lift-off distance

In this section, we report the results of coil lift-off for two specimens. One specimen is a 10 mm thick stainless steel specimen that is coated with the Fe_3O_4 layer, and the other is a 10 mm thick uncoated stainless steel specimen. The separation distance of the magnet from the coating is fixed at 20 mm, and the received signals are shown in Fig. 4(a), for different lift-off distances of the EMAT coil. Fig. 4(b) shows the received signals of an uncoated stainless

steel specimen under different lift-off distances of the EMAT coil. The separation distance between the magnet and the EMAT coil is fixed at 2 mm in Fig. 4(b) as the main transduction mechanism is Lorentz force in the stainless steel specimen, which requires a strong normal bias magnetic field. It can be seen that the temporal duration of the main bang decreases when the EMAT coil is closer to the stainless steel specimen. The reason is due to the decreasing coil inductance as eddy currents are induced in the surface of the stainless steel.

As shown in Fig. 4, the peak-to-peak value and signal-to-noise ratio (SNR) of the first shear wave has been marked. It should be noted that the gain in the experiment is the same at different lift-offs. SNR was calculated using Eq. (1), where SNR_{dB} is the signal-to-noise ratio in decibels, A_{signal} is the maximum signal amplitude within the echo, and A_{noise} is the average value of a number of noise peaks for a region of noise at the maximum effective lift-off distance. The region of noise used to calculate SNR is identified in each figure for reference.

$$SNR_{dB} = 20 \log_{10} \left(\frac{A_{signal}}{A_{noise}} \right) \quad (1)$$

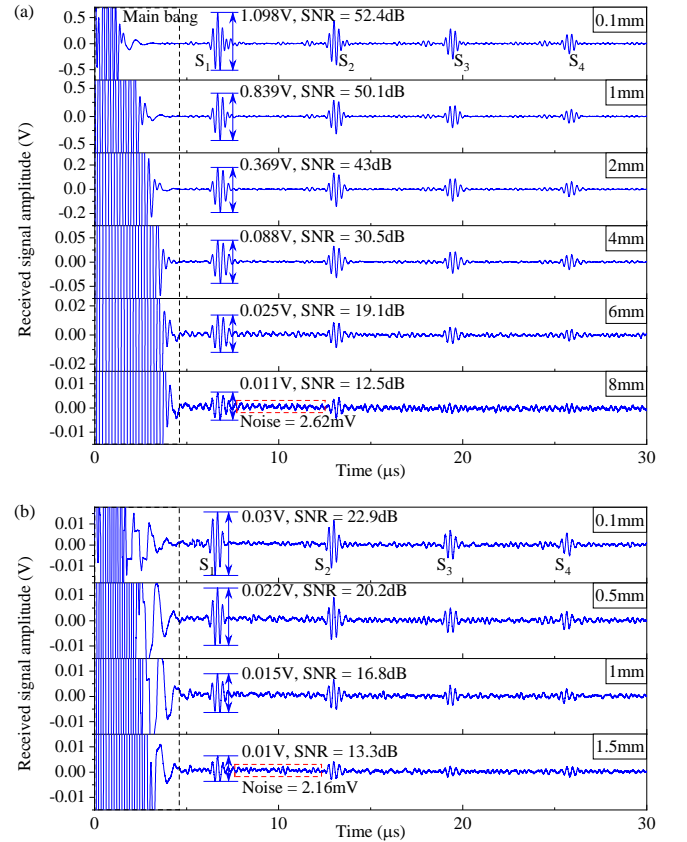


Fig. 4. Experimental results under different lift-off distances of the EMAT coil. (a) 10 mm thick coated stainless steel, and (b) 10 mm thick uncoated stainless steel.

The shear wave is still the dominant signal component in Fig. 4, and the maximum effective lift-off distance of the EMAT coil from the coating surface was 8 mm, on the coated stainless steel specimens. However, for the uncoated stainless steel specimen, the maximum effective lift-off distance of the EMAT coil was only 1.5 mm. In the coated stainless steel specimen, both the Lorentz force and magnetostriction mechanisms are involved in

the transduction process. Comparing Fig. 4(a) and Fig. 4(b), it can be seen that the Fe_3O_4 coating can indeed significantly enhance the lift-off operation distance of EMATs. The Fe_3O_4 coating is non-conductive, so the mechanism that enhances the lift-off performance is magnetostriction. Previous studies have proved that in specimens with very high magnetostriction coefficients, the magnetostriction mechanism can lead to very large amplitude ultrasonic signals and high signal-to-noise ratios [21]. The transduction efficiency of the EMAT at larger lift-off distances is directly related to the coating properties, and the influence of the electrical and magnetic properties of the actual test specimen (or substrate) can be ignored.

In summary, applying an Fe_3O_4 coating to test specimens can reduce the dependence of EMATs operation on the electrical and magnetic properties of the tested specimen and significantly improve the lift-off distance of EMAT at MHz ultrasonic excitation frequencies. The experimental results reported here will help to promote the application of coating technology in the field of electromagnetic ultrasonic testing. However, the underpinning science behind the physical properties of the Fe_3O_4 coating is not yet well understood: it now requires further work to study the B-H and field and frequency dependent magnetostriction behavior of the Fe_3O_4 coating, and the influences of the Fe_3O_4 powder particle size, and the mixture ratio of Fe_3O_4 powder and adhesive.

IV. CONCLUSION

This paper proposes a new method by applying Fe_3O_4 coating onto a test specimen's surface, to enhance the lift-off performance of EMATs. The coating material consists of Fe_3O_4 powder and an adhesive binder, which can be directly applied to the test specimen. Based on the experimental results, ultrasound can be successfully generated and received by EMATs through the Fe_3O_4 coating. Whilst there are alternative approaches such as the use of bonding electrically conductive or magnetostrictive metal patches to the specimen surface, they can be more difficult to implement on complex shaped parts, or parts with uneven or rough surfaces. Hence the evaluation of a coating approach that can be easily applied to any specimen merits investigation. From our investigations, the conclusion can be drawn as follows:

(1) The transduction efficiency of EMATs on an Fe_3O_4 coating is related to the bias magnetic field strength. When the vertical magnetic flux density is 0.12 T, the EMAT appears to have the highest transduction efficiency for the coil current pulse reported here on the particular coating investigated.

(2) The transduction process of EMATs on coated specimens at a larger lift-off distance is directly related to the magnetostrictive mechanism in the coating, and the influence of the electrical and magnetic properties of the test specimen itself can be ignored, when this substrate is not magnetostrictive.

(3) The Fe_3O_4 coating can significantly enhance the lift-off performance of EMATs, and the maximum effective lift-off distance of EMAT reported here is 8 mm on coated specimens.

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